Dark particles twinkle in hadronic calorimeters at future Higgs factories

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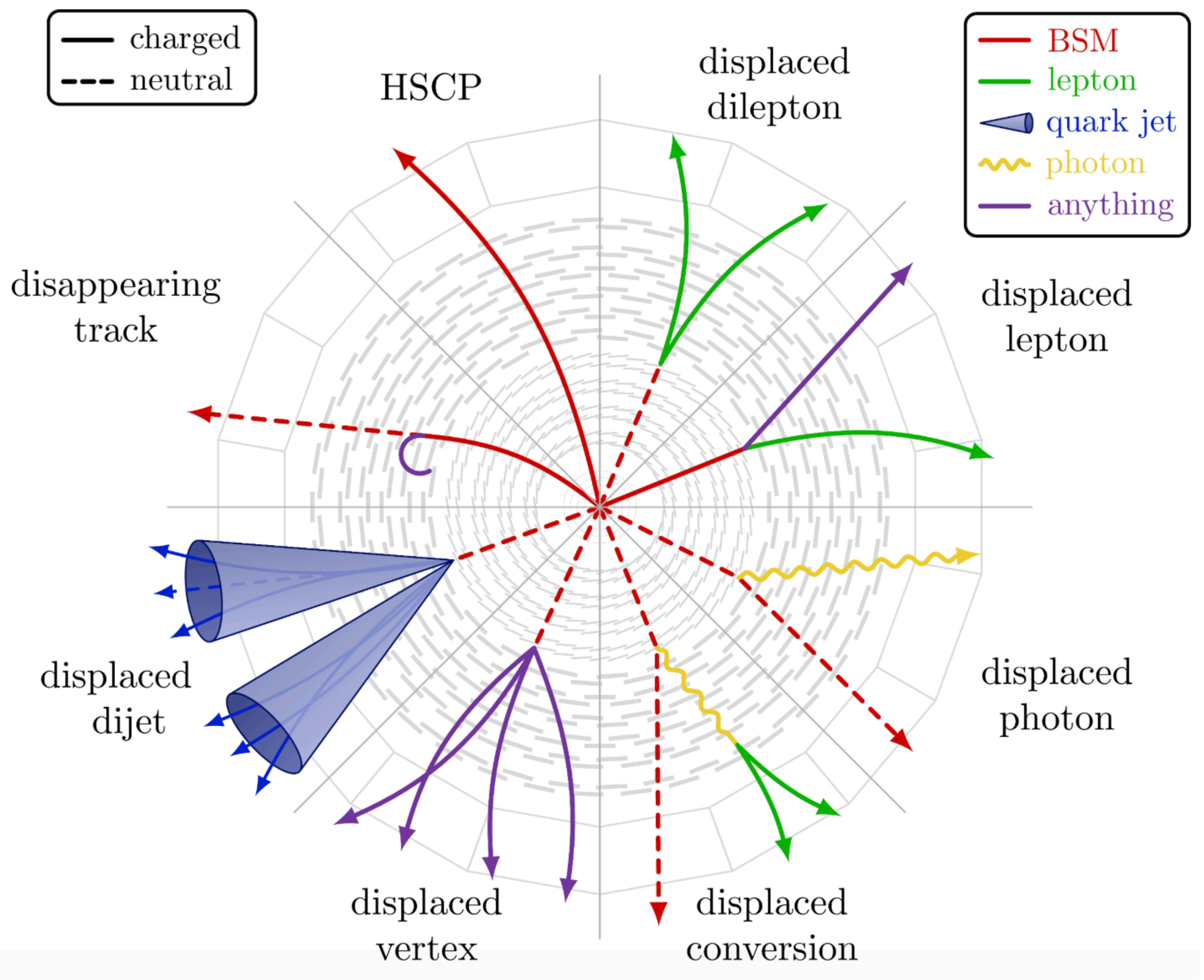
Long-lived particle (LLP) searches at colliders

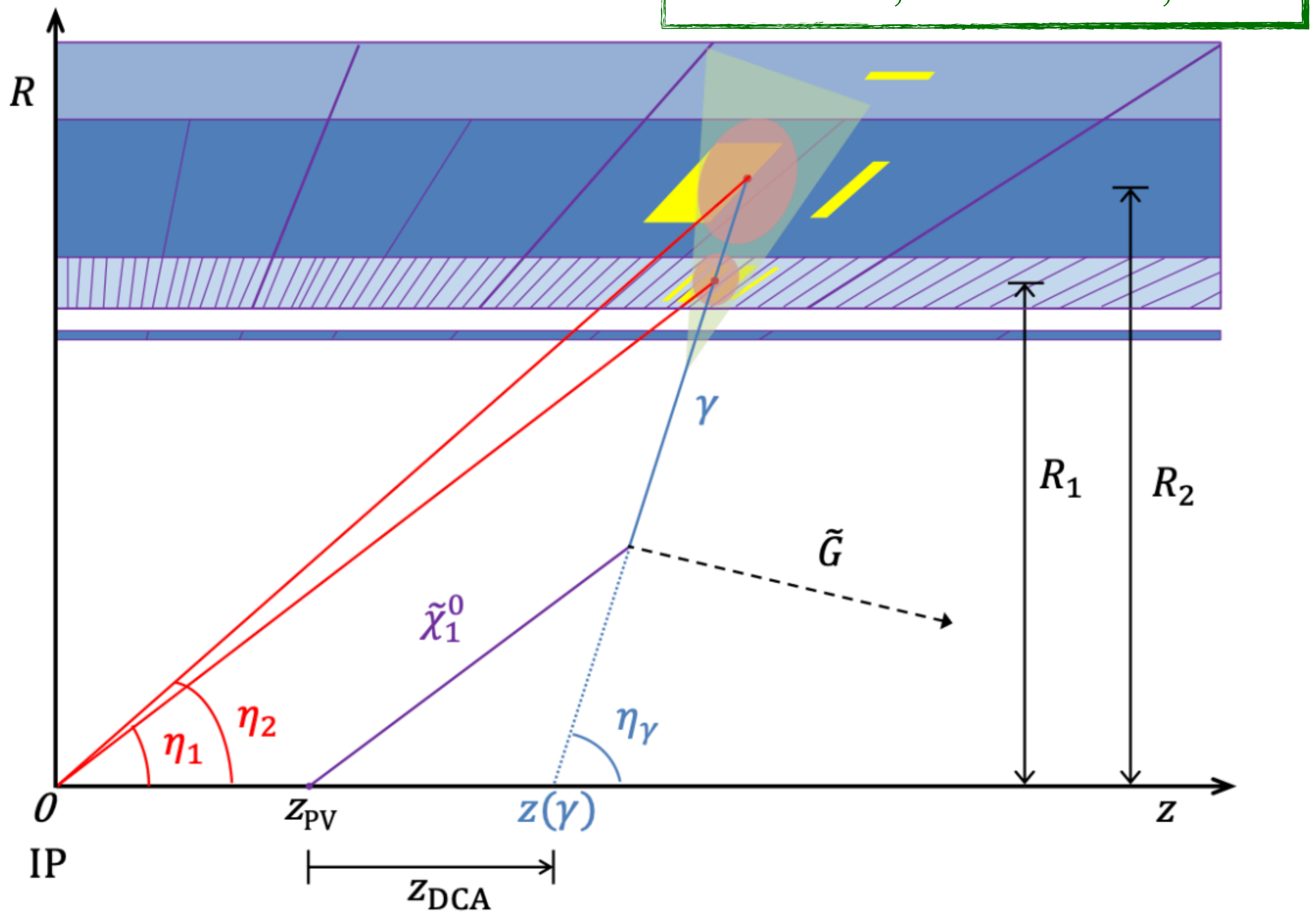
Decay into charged particles:
displaced dijet, displaced dilepton, displaced vertex…
(vertex detector, tracker)

Decay into neutral particles:
displaced photon (non-pointing photon)
(Multi-layer ECAL)



https://tikz.net/bsm_longlived/

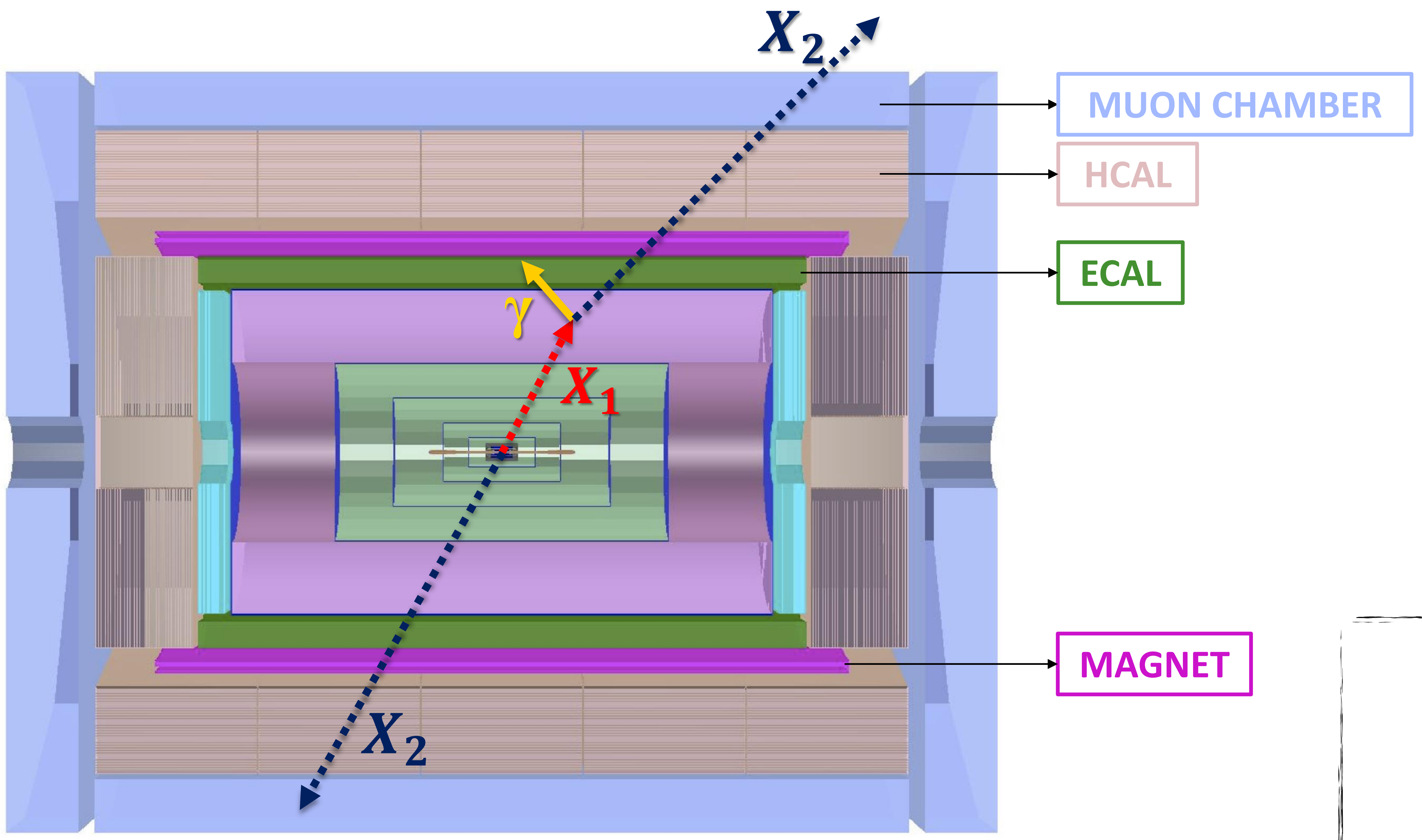
Nikiforou, PHD thesis, 2014



In general, displaced charged particles have cleaner backgrounds than displaced photons, thanks to the higher position resolution of the vertex detector and the tracker.

Large backgrounds for displaced mono-photon at future Higgs factories

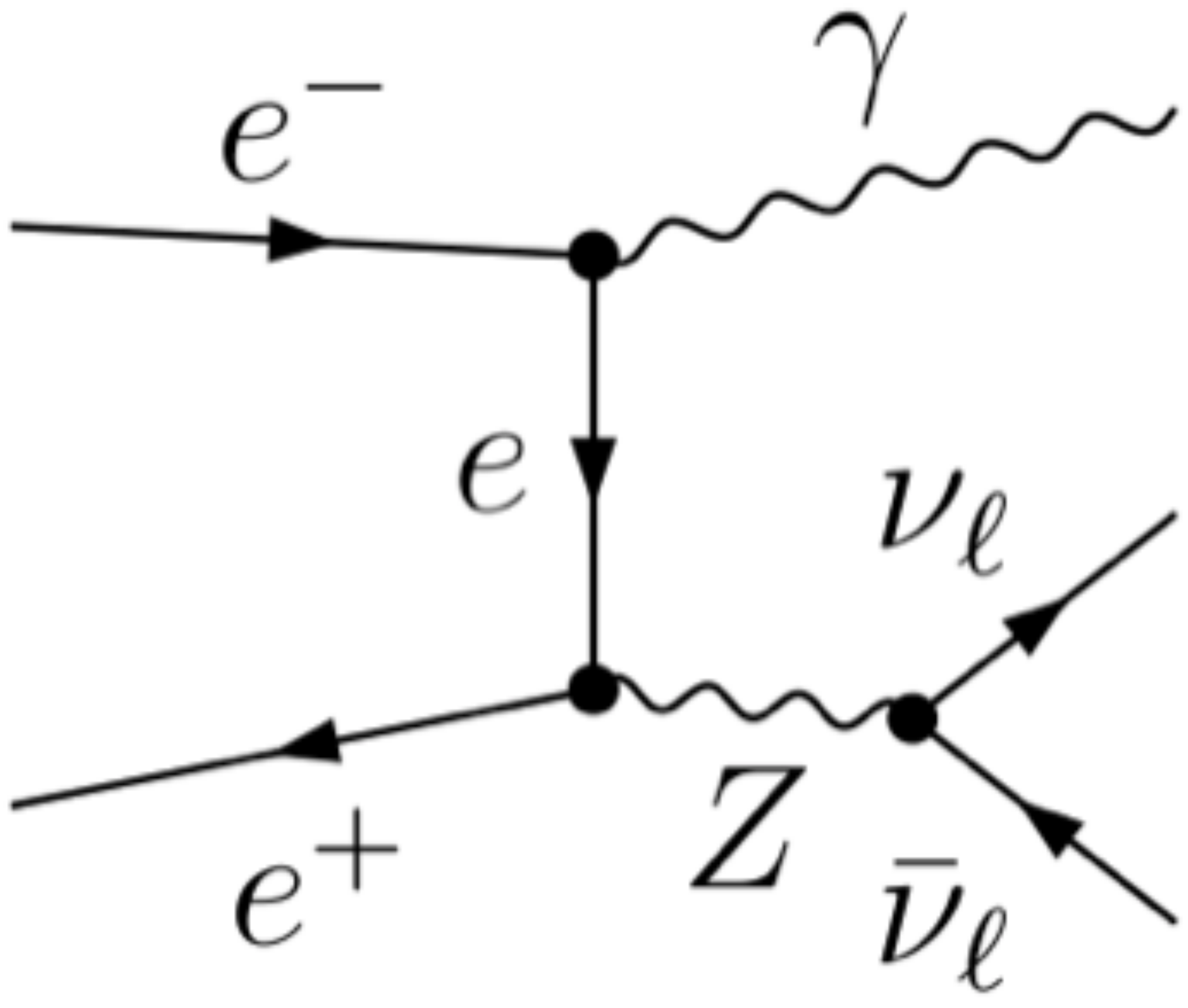
CEPC reference detector



$$e^+e^- \to X_1 X_2,\ X_1 \to X_2 \gamma$$

X_1: heavier dark sector particle

X_2: lighter dark sector particle or SM neutrino



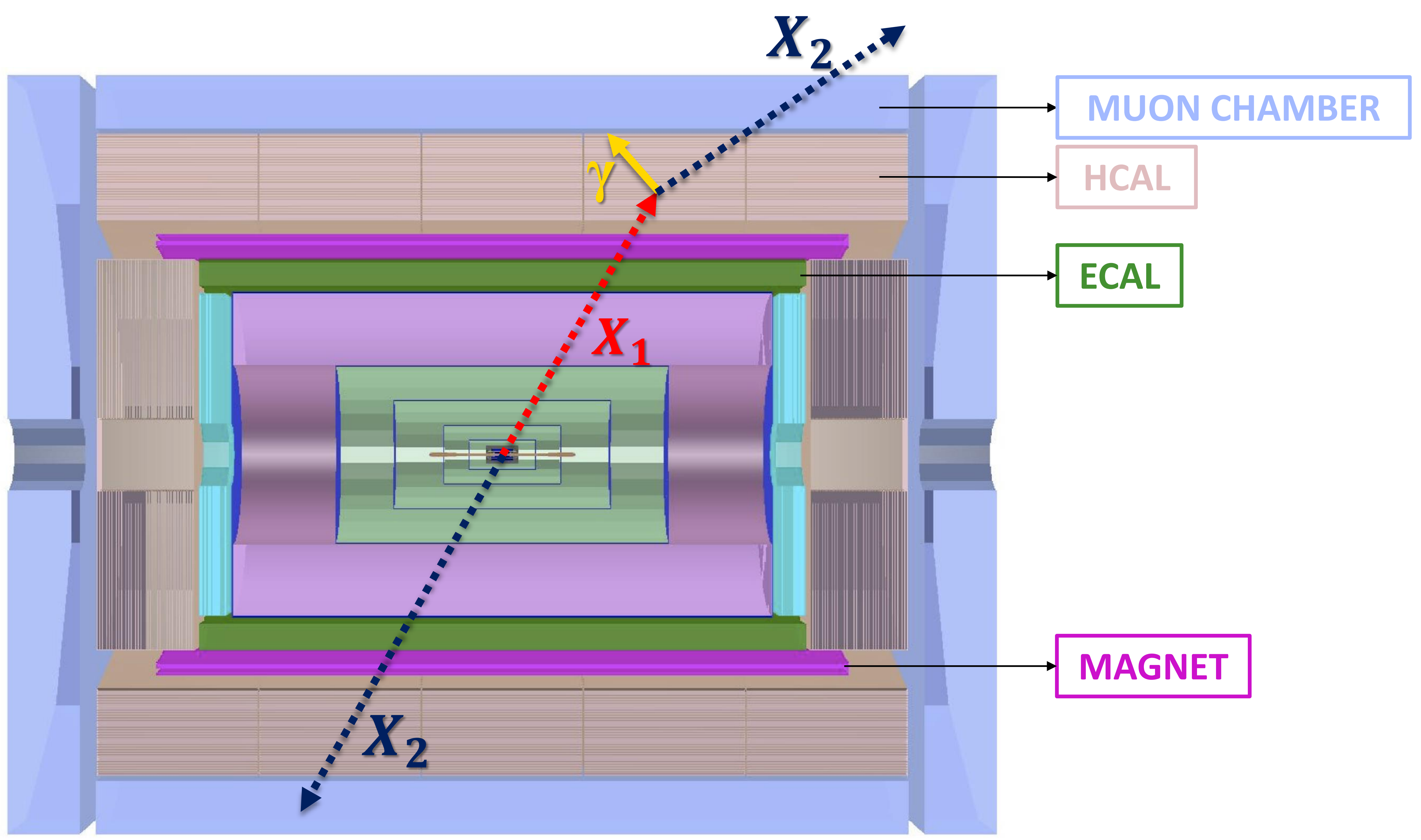
More than 10^{10} $e^+e^- \to \nu\bar{\nu}\gamma$ events with

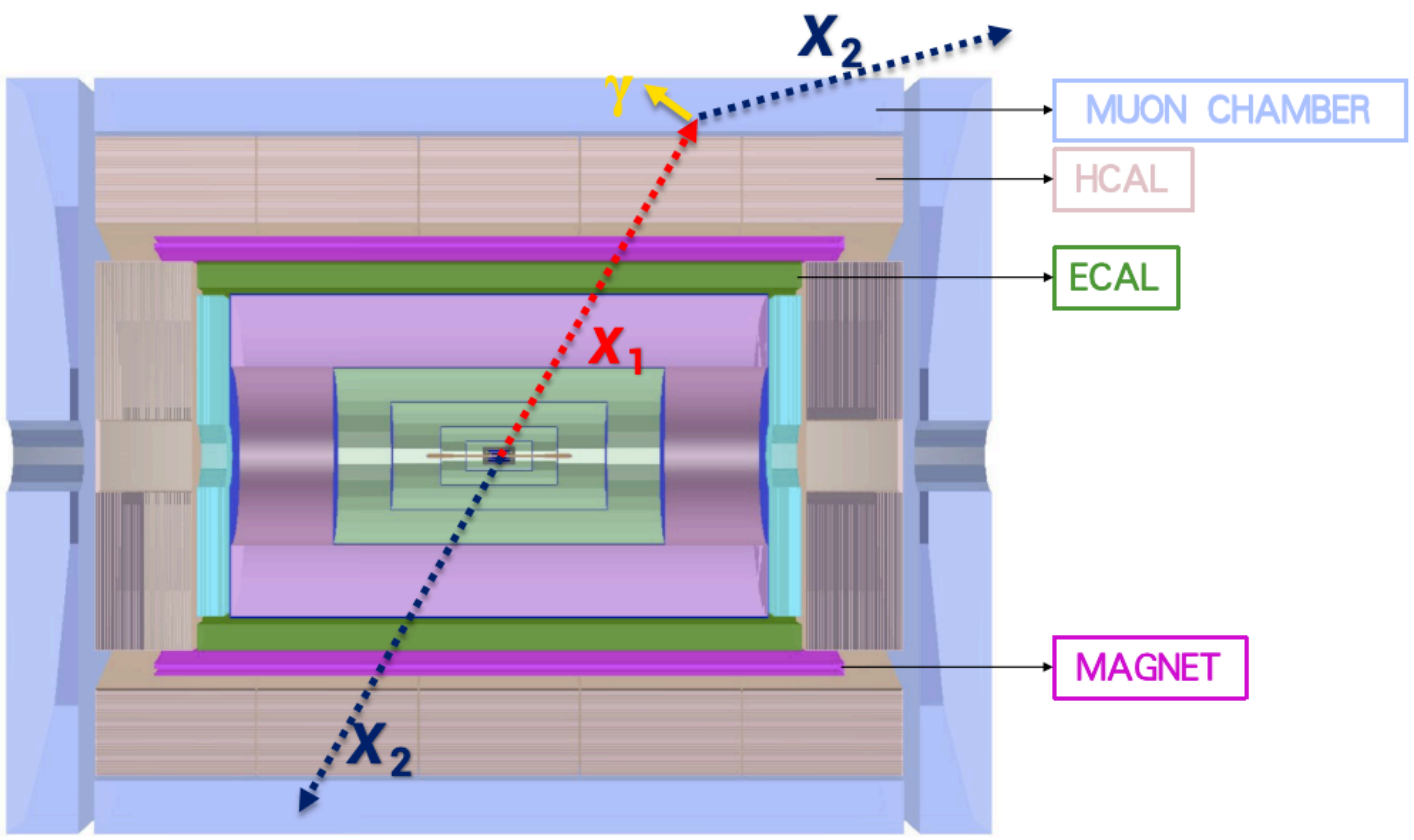
$$E_\gamma > 1\ \text{GeV}$$

for CEPC Z-mode with the luminosity of 100/ab

Displaced photons face substantial backgrounds unless high-granularity directional calorimetry is employed.

HCAL and the muon detector serving as photon far detectors





$$e^+e^- \to X_1 X_2,\ X_1 \to X_2 \gamma$$

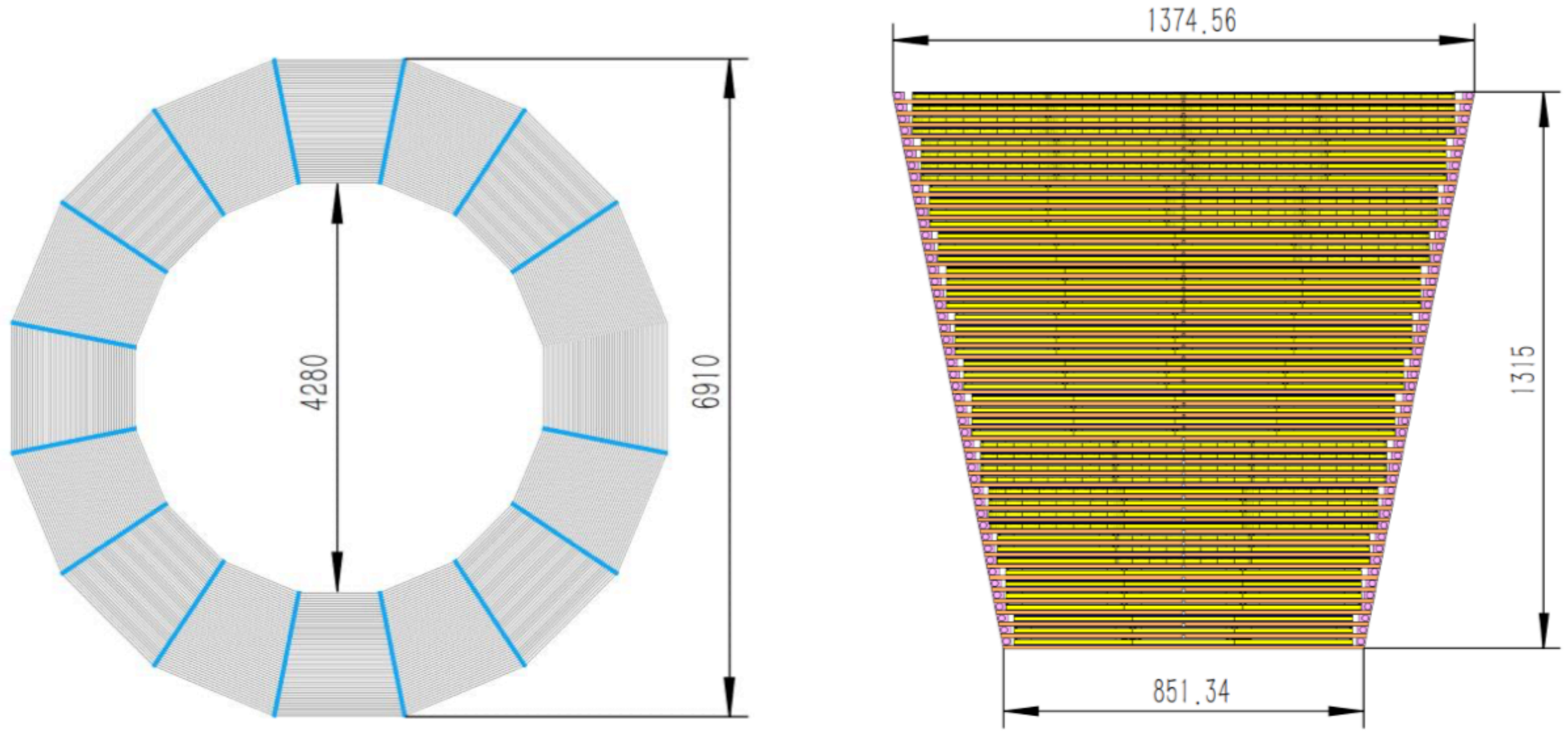
X_1: heavier dark sector particle

X_2: lighter dark sector particle or SM neutrino

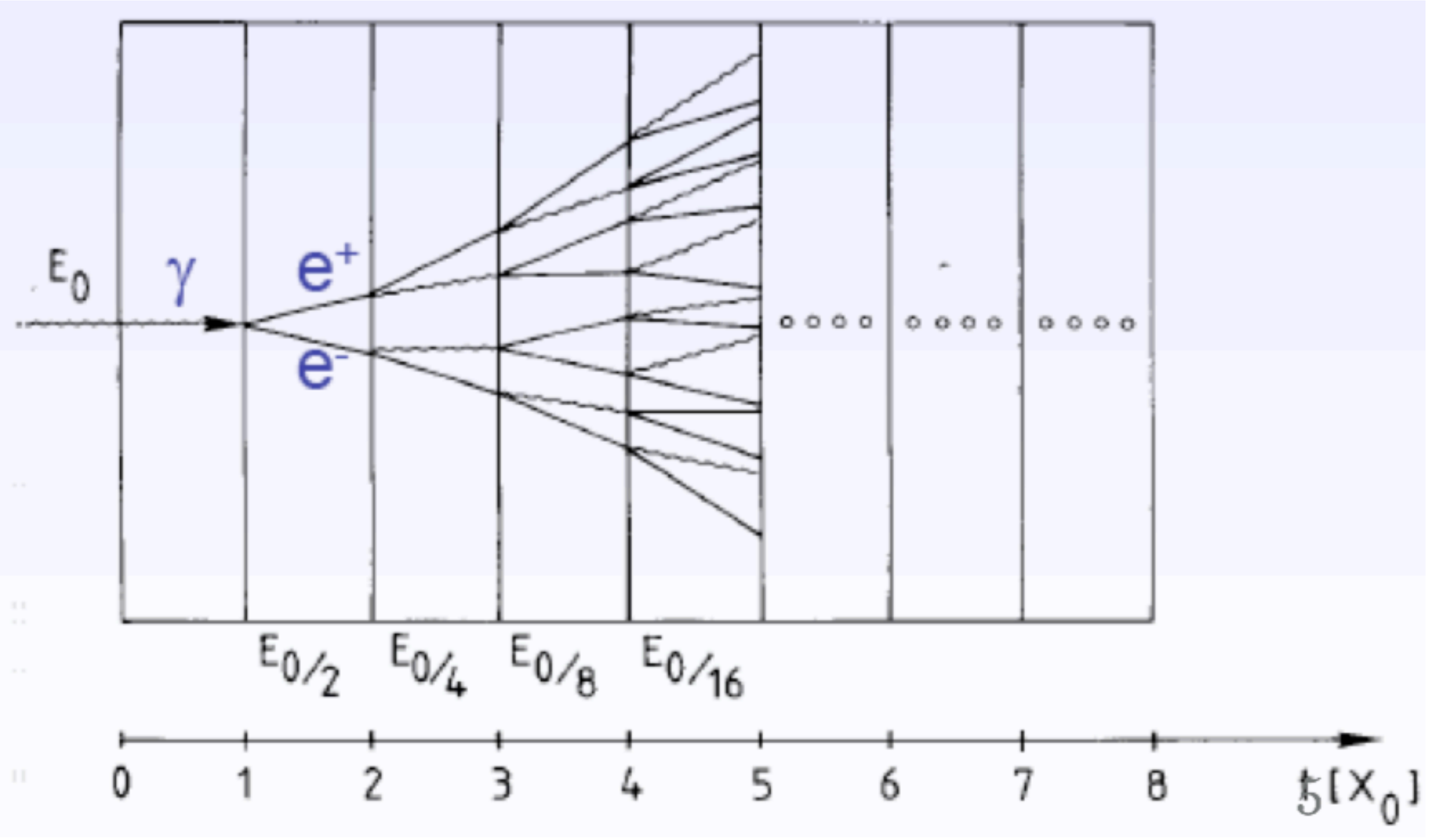
Using the ECAL as a shield against mono-photon backgrounds from the primary vertex and detecting displaced photons in the HCAL or muon detector.

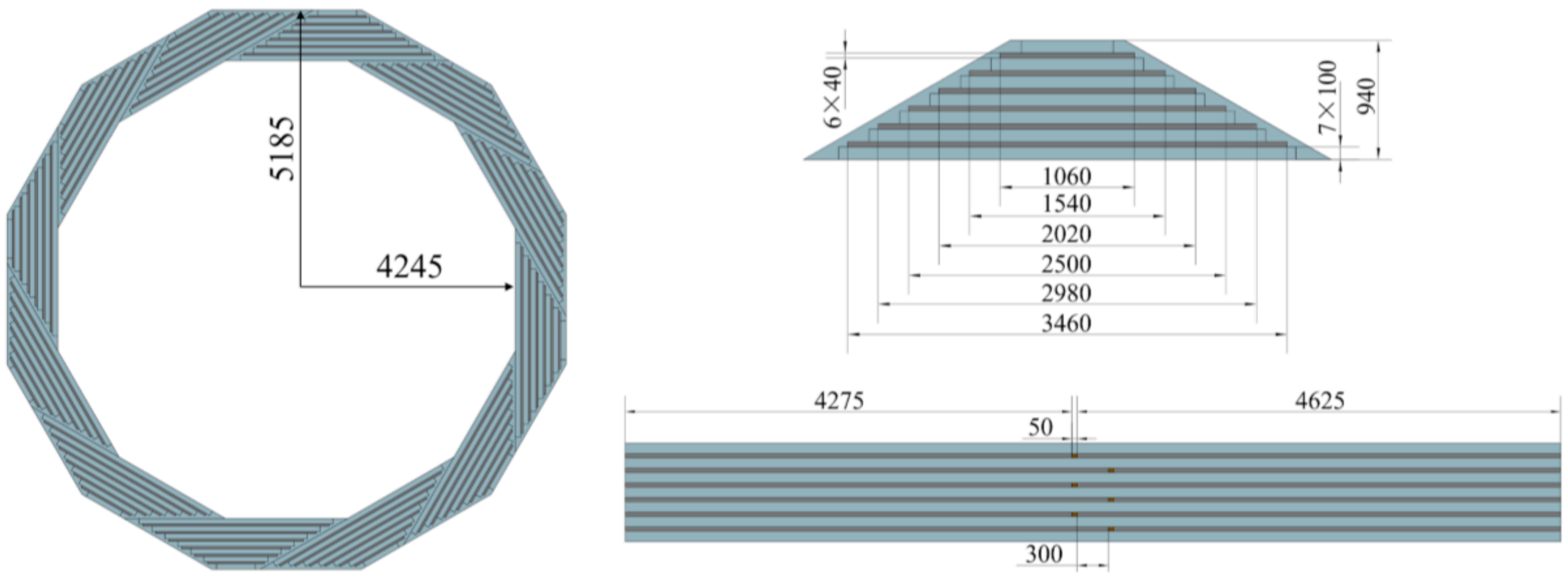
HCAL and the muon detector serving as photon far detectors

CEPC Ref-TDR



HCAL

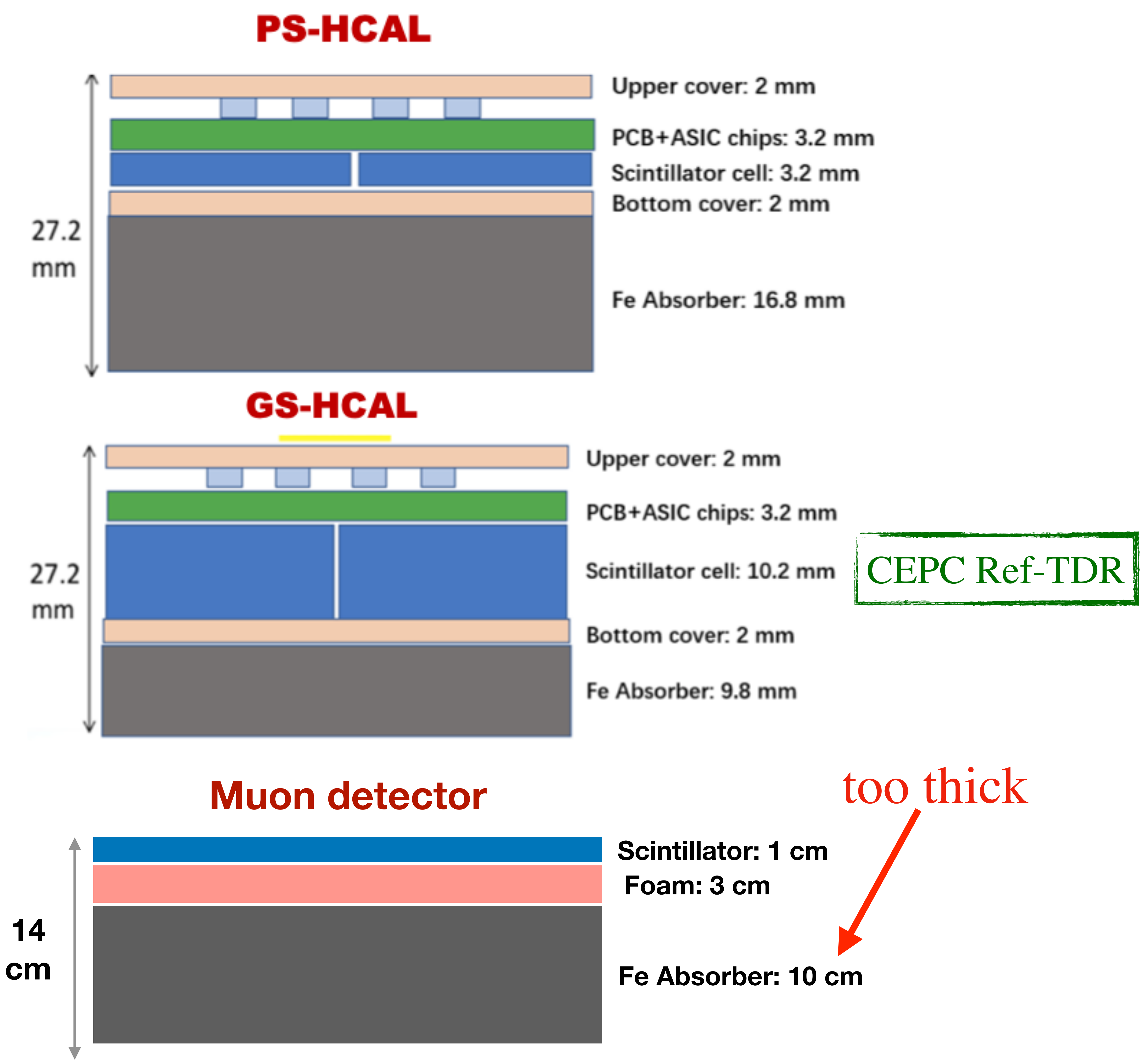




Muon detector

Both the HCAL and the muon detector are sampling detectors with a sandwich structure of iron plates and scintillators, when considered as detectors for photons.

The HCAL serving as a photon far detector



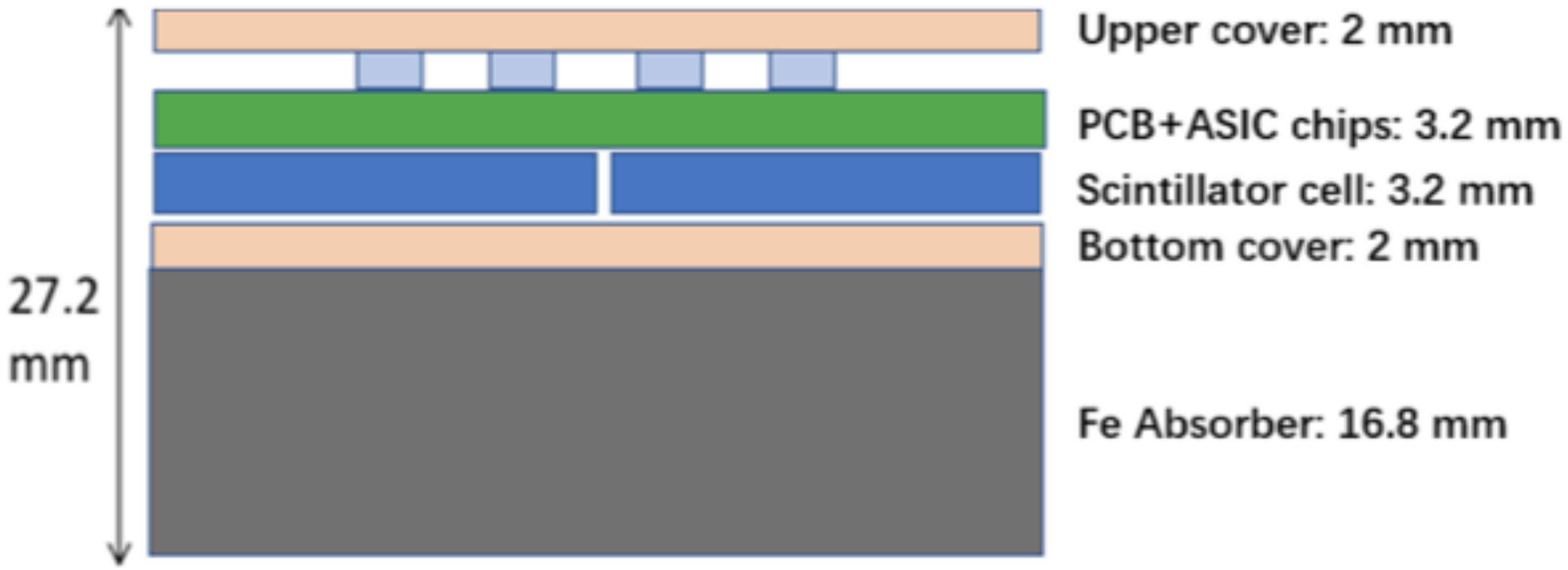
$$E_\gamma^{\min} = 2^t \times E_c, t = L/X_0$$

Detector	PS-HCAL	GS-HCAL	Muon detector
Main components per layer	20.8 mm Fe	13.8 mm Fe 10.2 mm GS	10 cm Fe
t (radiation length per layer)	1.21	1.44	5.68
Critical energy	~20.7 MeV	~15.7 MeV	~20.7 MeV
Energy threshold for five layers	1.37 GeV	2.30 GeV	7332 TeV
	✓	✓	✗

We can only use the HCAL to detect photons, either GS-HCAL or PS-HCAL, provided that energy is deposited in at least five active layers.

The GS-HCAL serving as photon far detectors

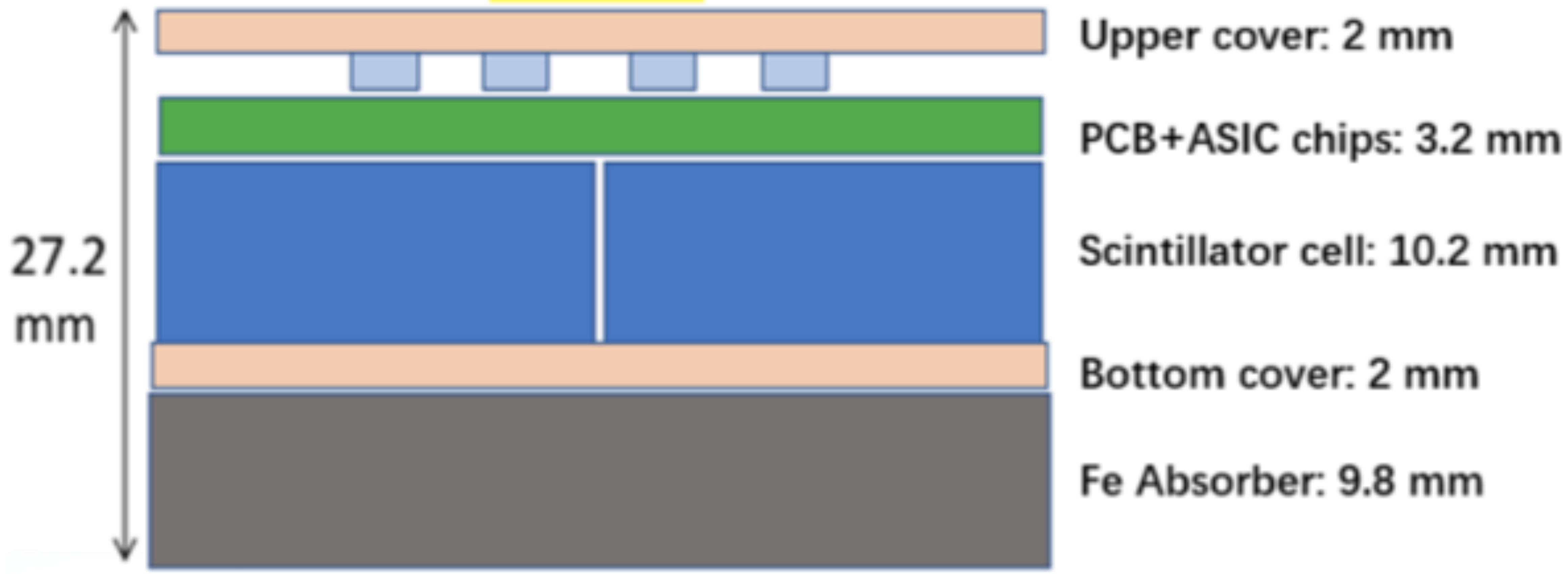
PS-HCAL



Sampling fraction ~1.6% (π^-, MC)

GS-HCAL

CEPC Ref-TDR



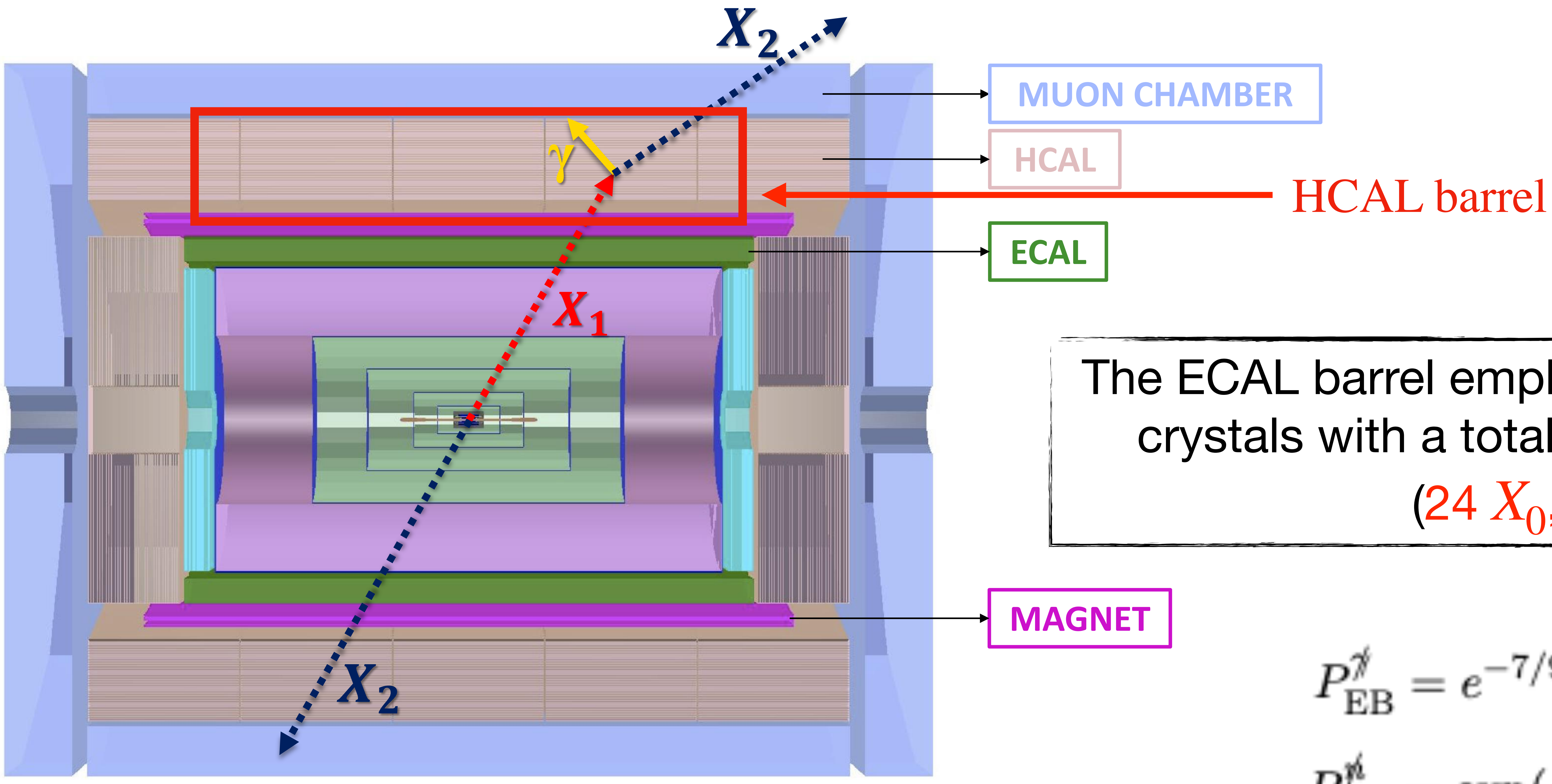
Sampling fraction ~31%

With high density and thick GS cell design, the sampling fraction of GS-HCAL can be increased by a factor of ~20 compared to that of PS-HCAL.

↓

We take the GS-HCAL as the benchmark detector for photons originating from LLP decays and assume a 50% reconstruction efficiency.

GS-HCAL barrel serving as a photon far detector



The ECAL barrel employs homogeneous BGO crystals with a total thickness of 300 mm ($24\ X_0$, $1.35\ \lambda_I$).

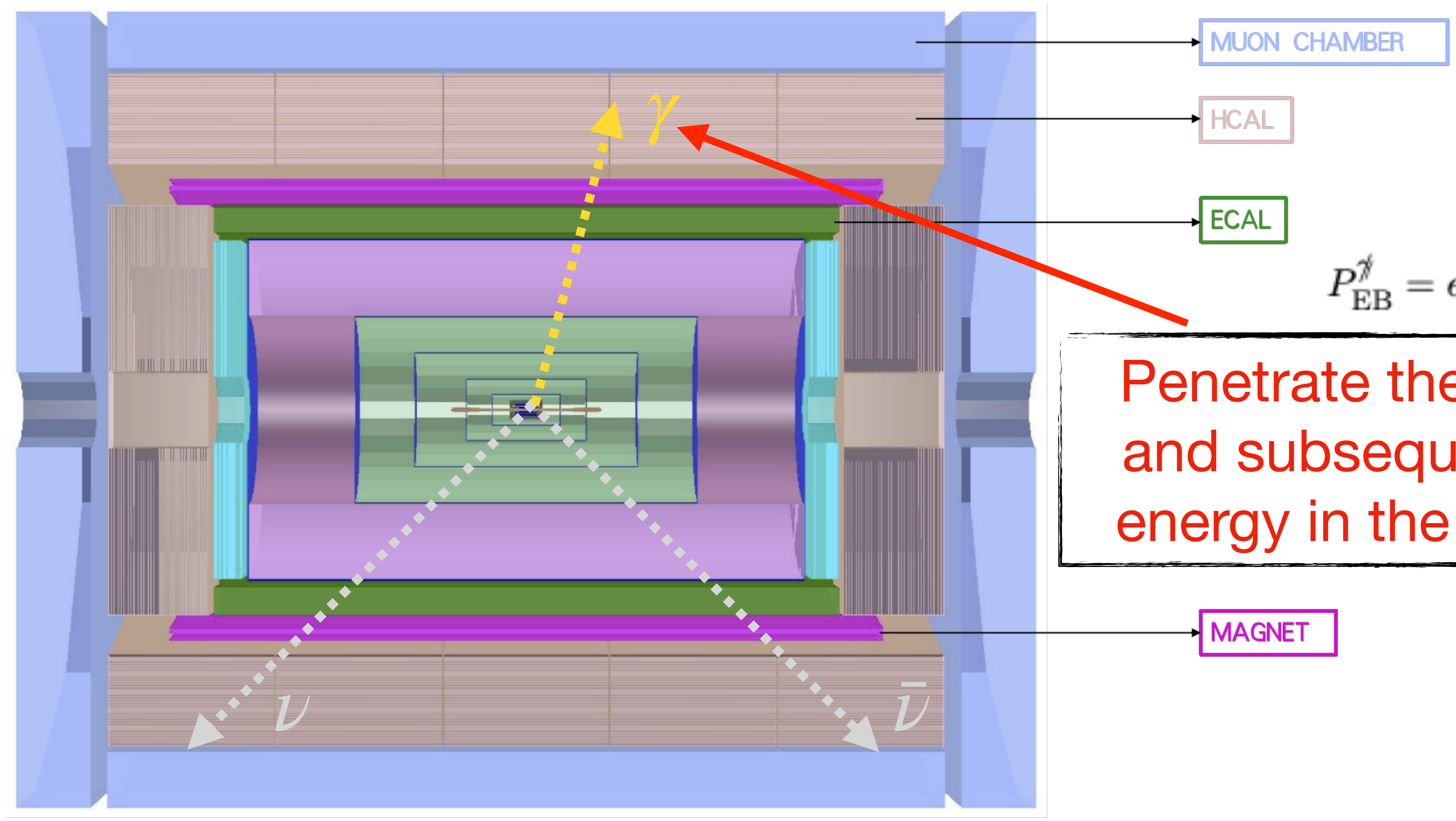
$$P_{\rm EB}^{\not\gamma} = e^{-7/9\times 24} = 7.8\times 10^{-9}$$

$$P_{\rm EB}^{\not h} = \exp(-1.35) = 0.26$$

The HCAL barrel is surrounded by ECAL, HCAL endcaps, and muon detector, which together provide strong veto capabilities against beam-related backgrounds, cosmic rays, and neutral particles from the primary interaction.

Backgrounds

- Photon backgrounds
- Neutrino backgrounds
- Neutral hadron backgrounds



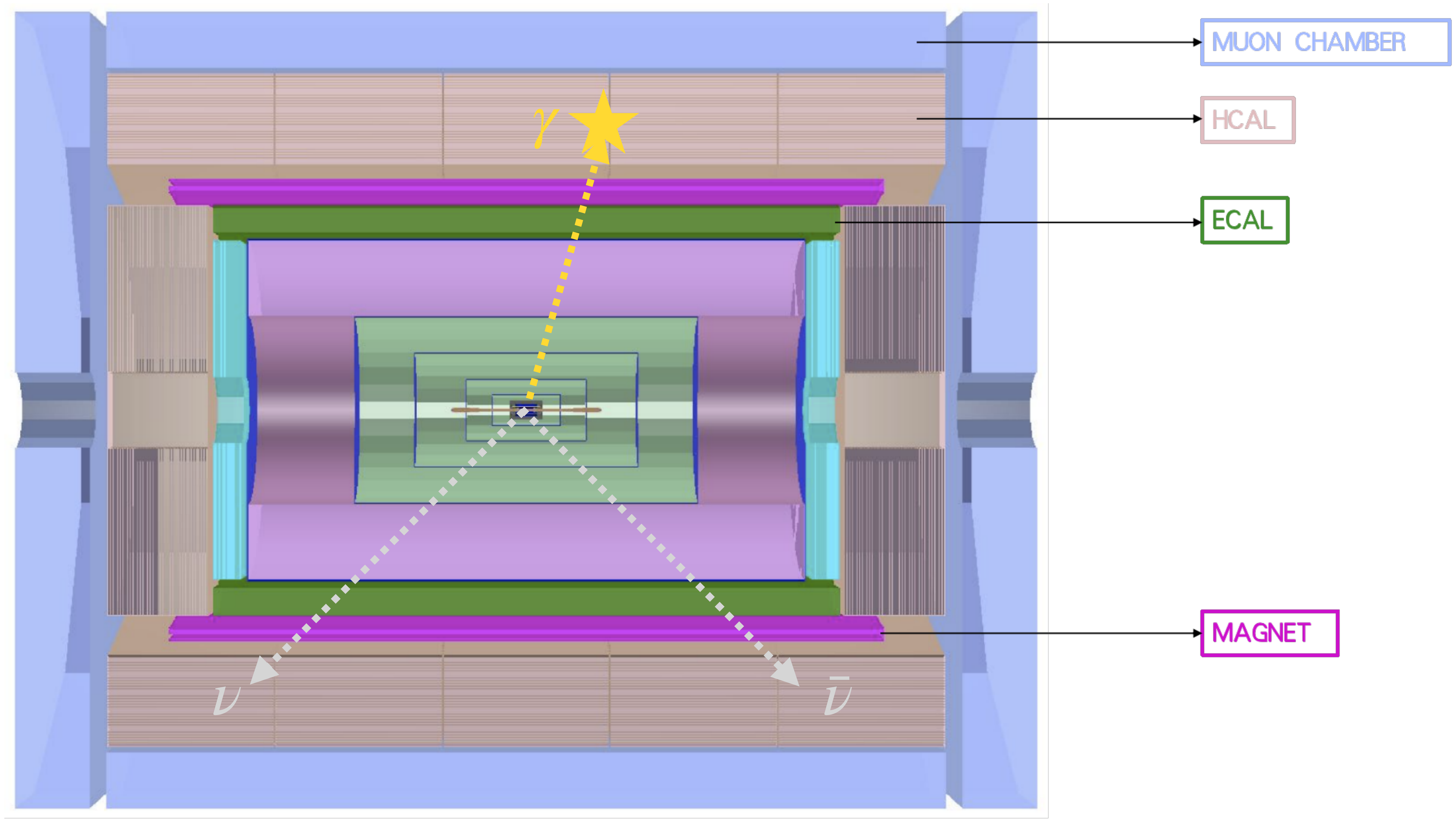
$$P^{\not\gamma}_{\mathrm{EB}} = e^{-7/9\times 24} = 7.8 \times 10^{-9}$$

Penetrate the ECAL barrel and subsequently deposit energy in the HCAL barrel.

The dominant SM backgrounds for the HCAL-γ_d signature originate from single photons, neutrinos, or neutral hadrons produced at the primary vertex without any accompanying detectable particles.

These neutral particles evade detection in the inner tracker and ECAL, and subsequently deposit energy in the HCAL barrel.

Photon Backgrounds



Z-mode, 100/ab

$$N_{e^+e^- \to \nu\bar{\nu}\gamma} = 1.34 \times 10^9$$

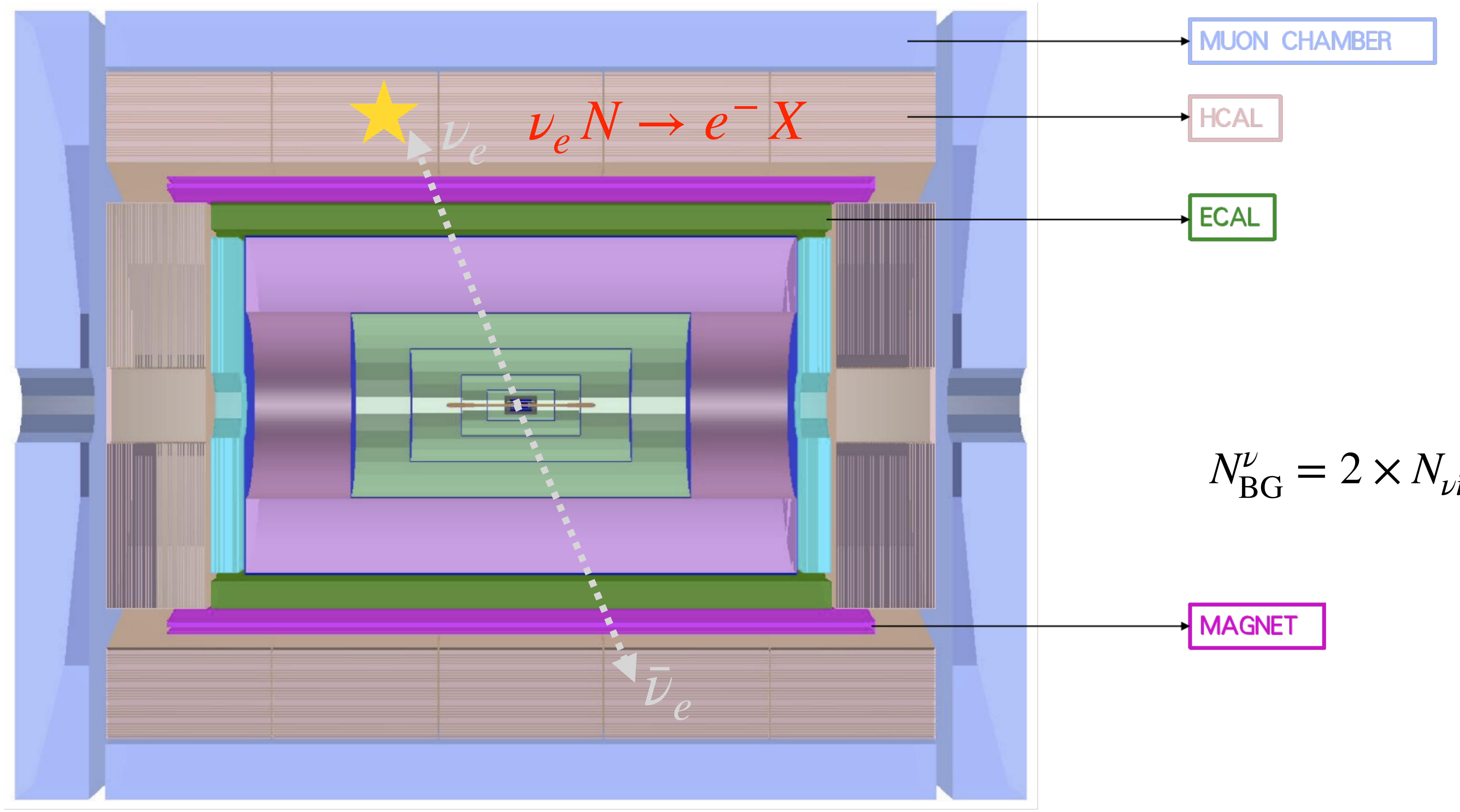
$$E_\gamma > 2.3\,\mathrm{GeV}$$

$$P_{\mathrm{EB}}^{\not\gamma} = e^{-7/9 \times 24} = 7.8 \times 10^{-9}$$

$$N_{\mathrm{BG}}^{\gamma} \sim 10$$

The photon-induced backgrounds can be reduced to a negligible level if using the first few layers of the HCAL barrel as vetoes.

Neutrino Backgrounds



Z-mode, 100/ab

$N_{\nu_e\bar{\nu}_e} = 4.1 \times 10^9$

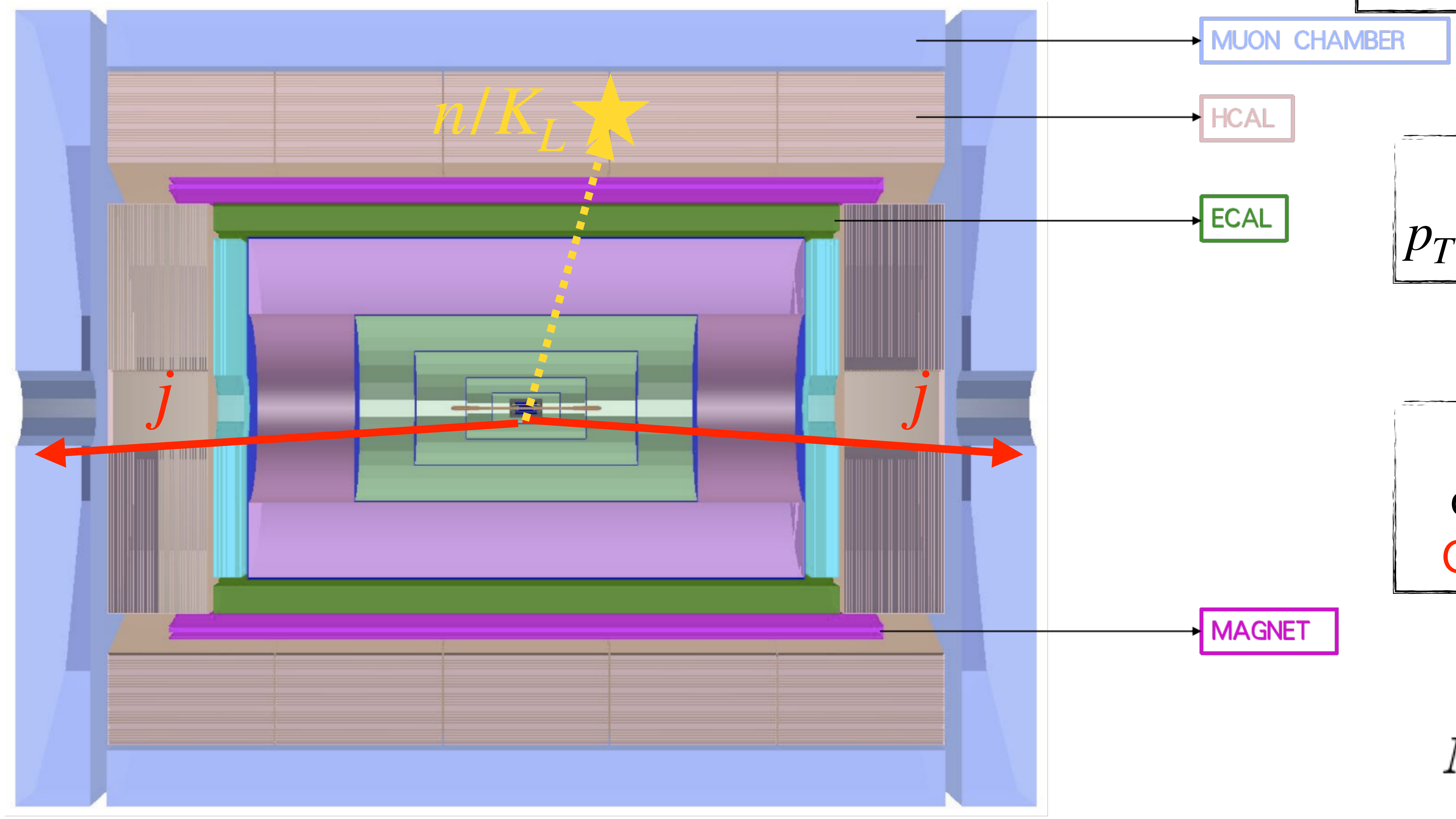
FASER Collaboration, EPJC (2020) 80:61

$$N_{\mathrm{BG}}^{\nu} = 2 \times N_{\nu\bar{\nu}} \times 4 \times 10^{-13} \times \frac{E_\nu}{\mathrm{GeV}} \times \left(\frac{L_{\mathrm{HB}}}{\mathrm{m}} \times \frac{\rho_{\mathrm{HB}}}{\rho_{\mathrm{H_2O}}}\right)$$

$$N_{\mathrm{BG}}^{\nu} \sim 1$$

The neutrino-induced backgrounds are negligible.

Neutral hadron Backgrounds



Simulate 10^8 $e^+e^- \to jjj$ events with $p_T^{j_1} > 1\,\mathrm{GeV}$, $p_T^{j_2,j_3} < 10\,\mathrm{GeV}$, and $\Delta R_{2j} > 0.4$
$\sigma_{3j} = 3300$ pb

Veto events if there are trakcs with $p_T > 0.1\,\mathrm{GeV}$ or photons with $E_\gamma > 0.1\,\mathrm{GeV}$

Select events with only one neutron or K_L within the HCAL barrel.
Only one event is found (large uncertainty).

$$N_{\mathrm{BG}}^{n,K_L} \simeq \frac{1}{10^8} \times \sigma_{3j} \times \mathcal{L} \times P_{\mathrm{EB}}^{\not\gamma} = 858$$

The electromagnetic showers induced by photons differ markedly from those of hadrons. Hence, with full exploitation of the high granularity and high sampling fraction of the GS-HCAL, neutral hadron backgrounds can be effectively suppressed.

Particle flow algorithms?

Backgrounds

$N_{\mathrm{BG}}^{\gamma} \sim 10,\, N_{\mathrm{BG}}^{\nu} \sim 1,\, N_{\mathrm{BG}}^{n,K_L} \sim 858$

$N_{\mathrm{BG}}^{\mathrm{tot}} \sim 10^3$

Optimistic estimation

$N_{\mathrm{BG}}^{\mathrm{tot}} \sim 10^2$

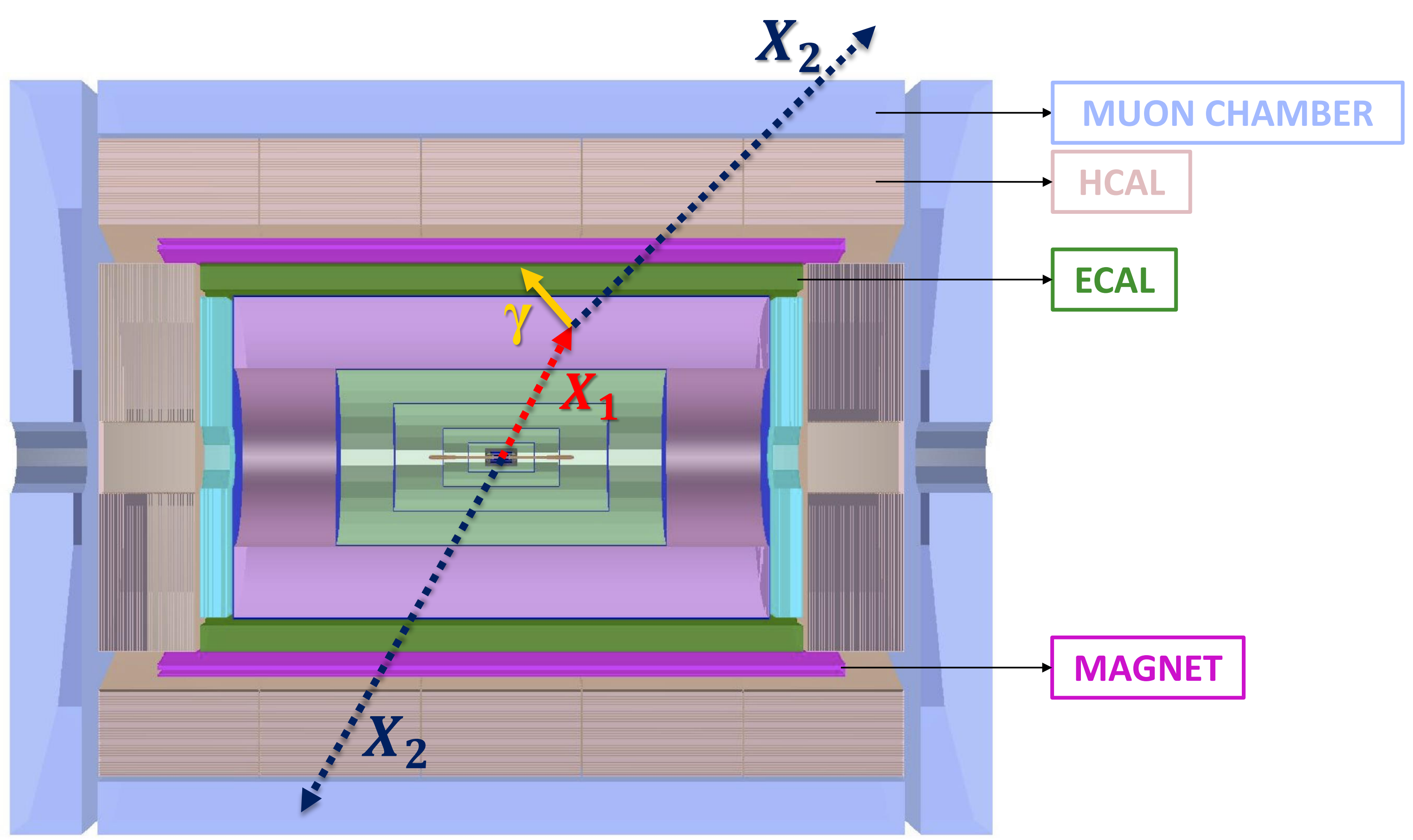
Conservative estimation

$N_{\mathrm{BG}}^{\mathrm{tot}} \sim 10^4$

2σ sensitivity: $N_s = 2\sqrt{N_{\mathrm{BG}}^{\mathrm{tot}}}$

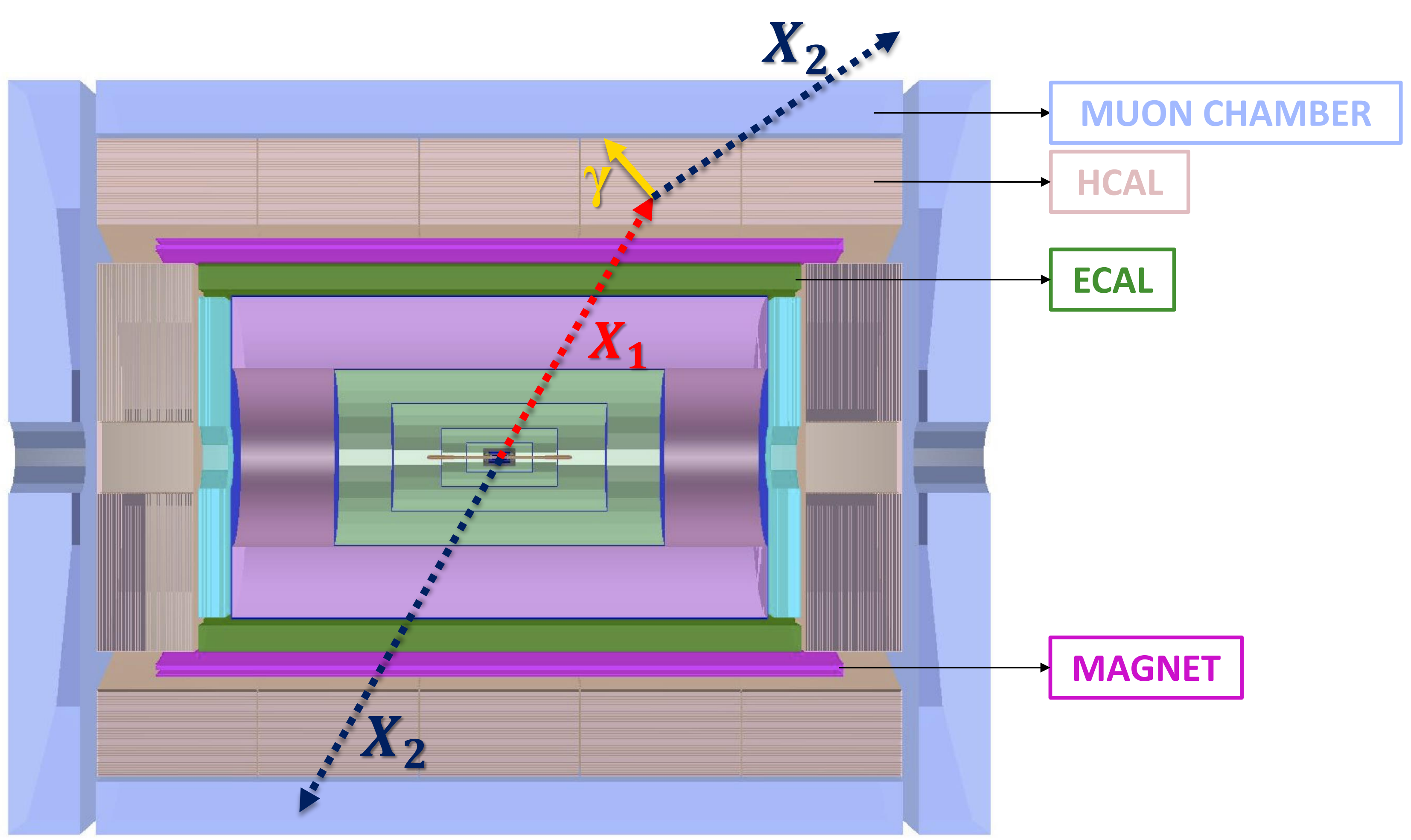
Three mono-photon signatures

$L_D \ll R_{\text{HCAL}}$



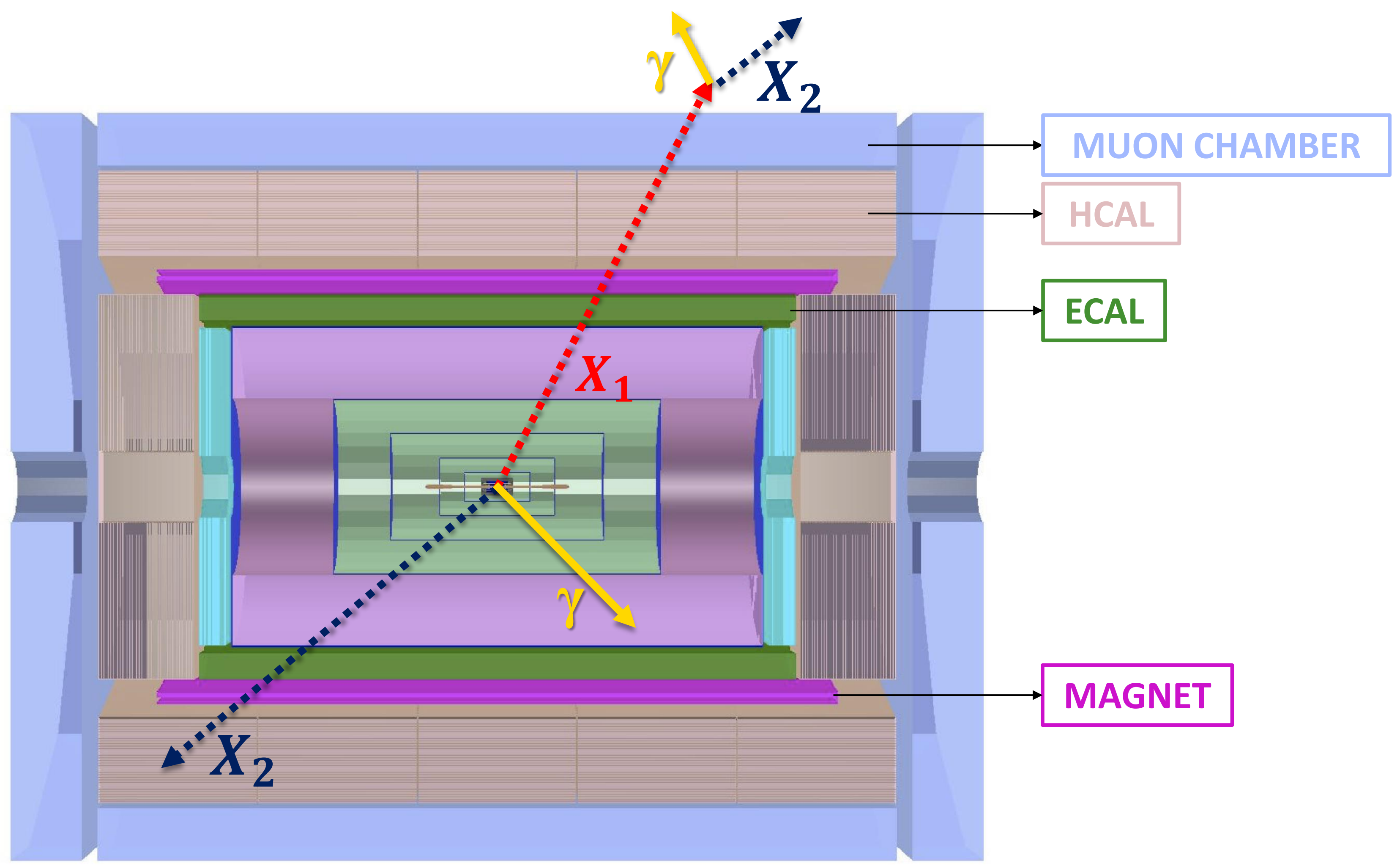
ECAL-γ_d

$L_D \sim R_{\text{HCAL}}$



HCAL-γ_d

$L_D \gg R_{\text{HCAL}}$



ECAL-γ_r

$$e^+e^- \to X_1X_2, X_1 \to X_2\gamma_d$$

γ_d: generated by X_1 decay

$$e^+e^- \to X_1X_2\gamma_r, X_1 \to X_2\gamma_d$$

γ_r: generated by ISR

Three mono-photon signatures give complementary sensitivities on photon portal LLPs.

Axion portal operator

$$\mathcal{O}_{a\gamma' B} \equiv g_B\, a \tilde{F}'_{\mu\nu} B^{\mu\nu}$$

a: axion like particle

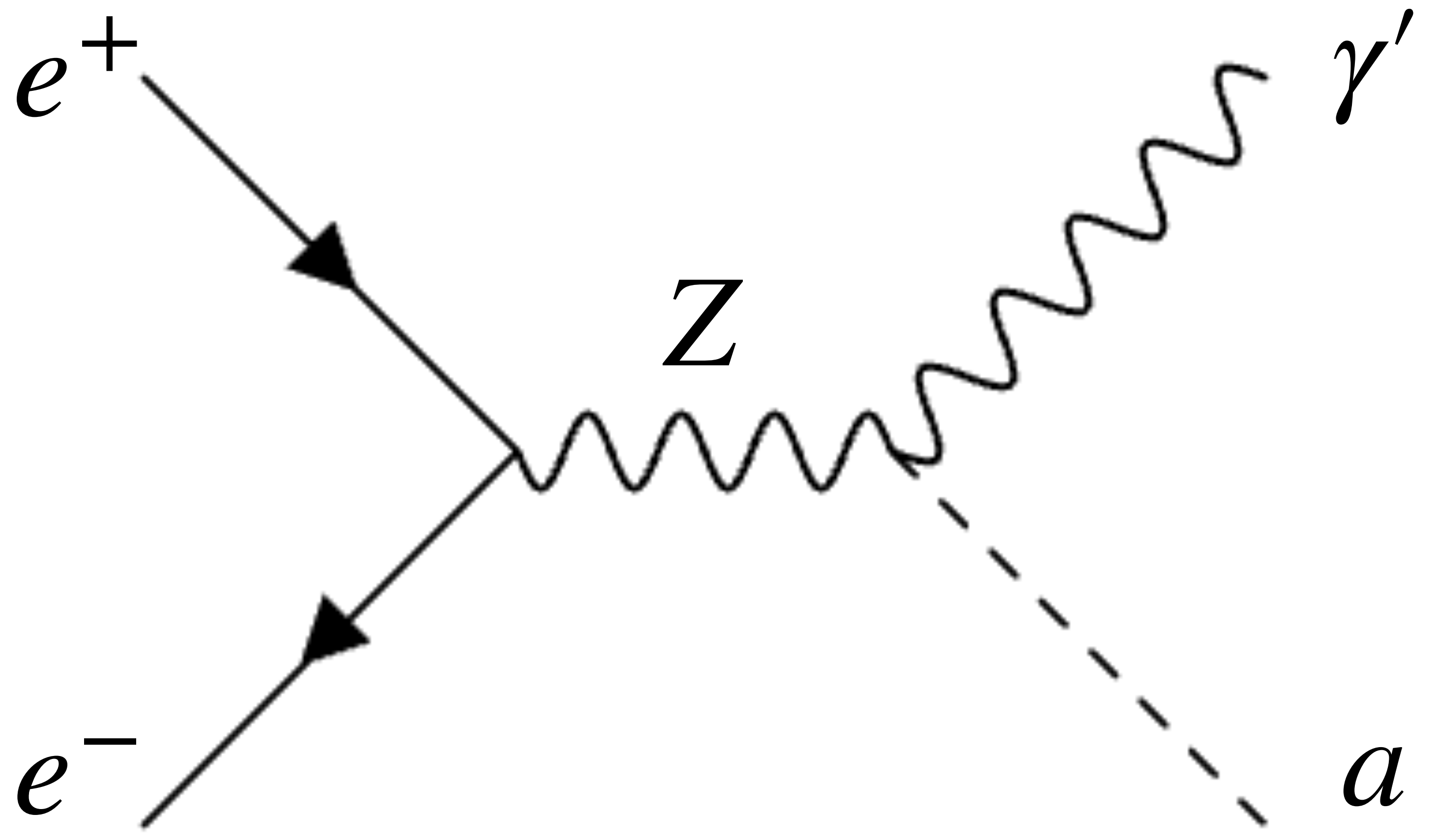
$F'_{\mu\nu}$: the field-strength tensor of the dark photon γ'

$B_{\mu\nu}$: the hypercharge field-strength tensor

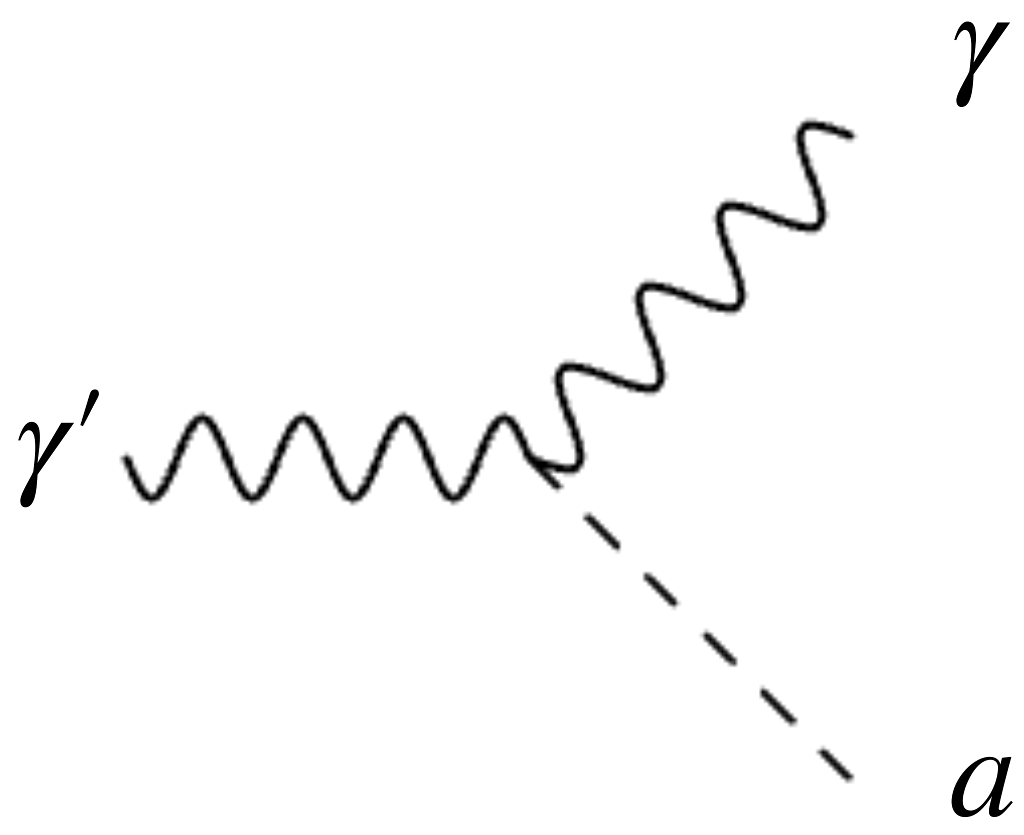
$$m_Z > m_{\gamma'} > m_a$$

$$\Gamma_{\gamma' \to a\gamma} = \frac{1}{24\pi} g_B^2\, c_W^2\, m_{\gamma'}^3 (1 - r_m^2)^3$$

$$E_\gamma^{\max} \simeq \frac{\sqrt{s}}{2}(1 - r_m^2),\ r_m = m_a/m_{\gamma'}$$



Generation process



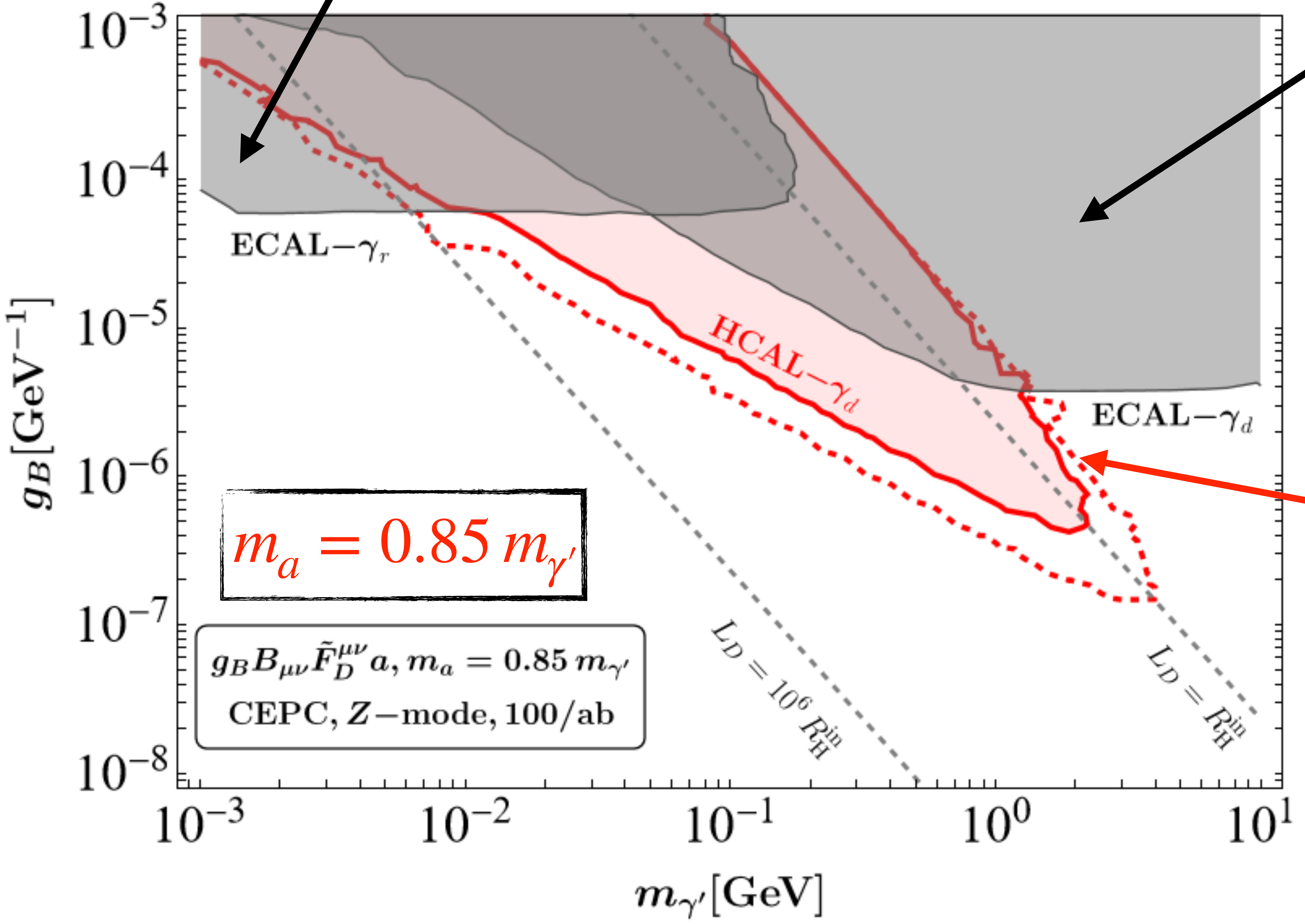
Decay process

CEPC sensitivities on axion portal operator

$L_D \gg R_H^{in}$

$L_D \ll R_H^{in}$

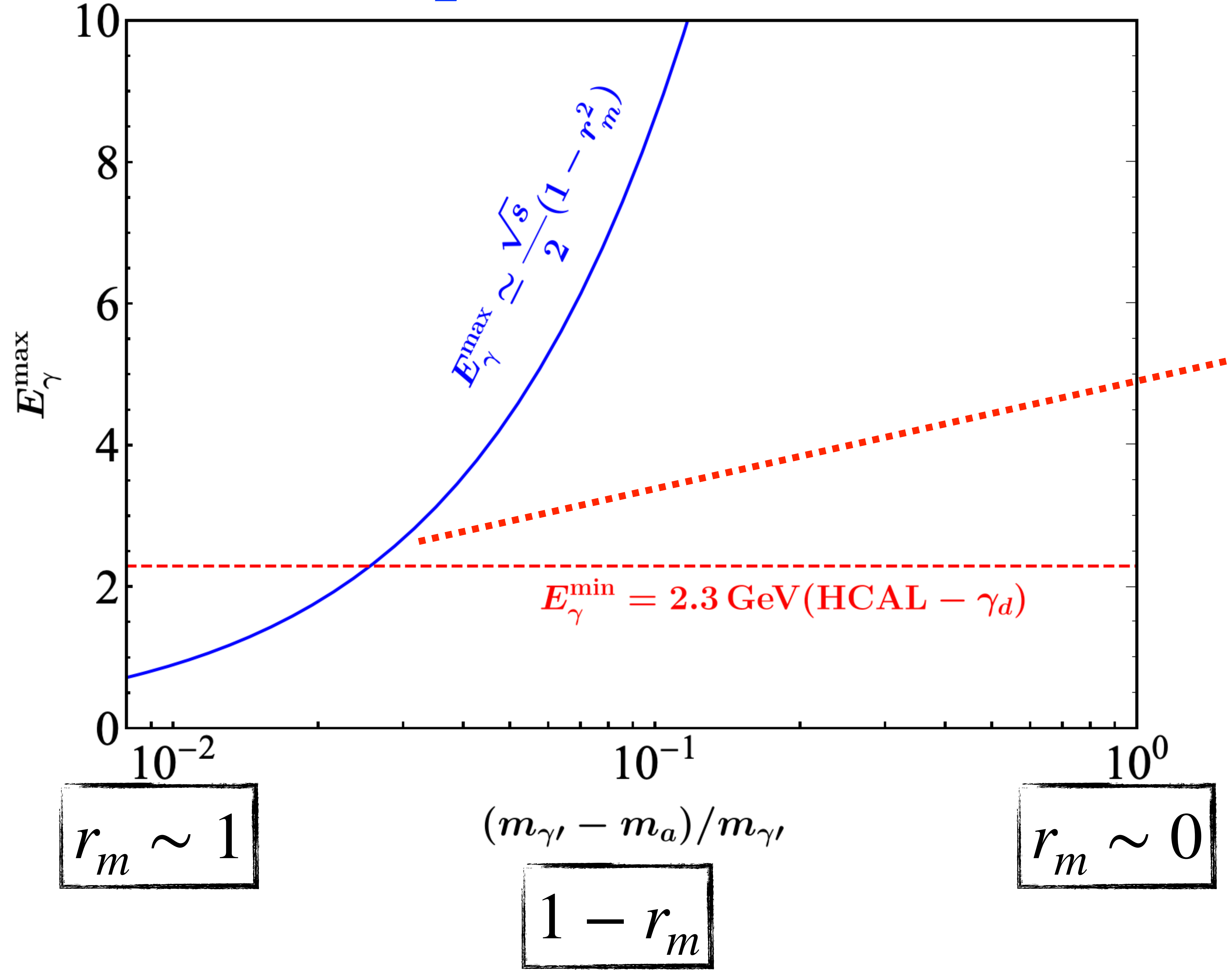
Inner radius of the HCAL
$R_H^{in} = 2.14\,\mathrm{m}$

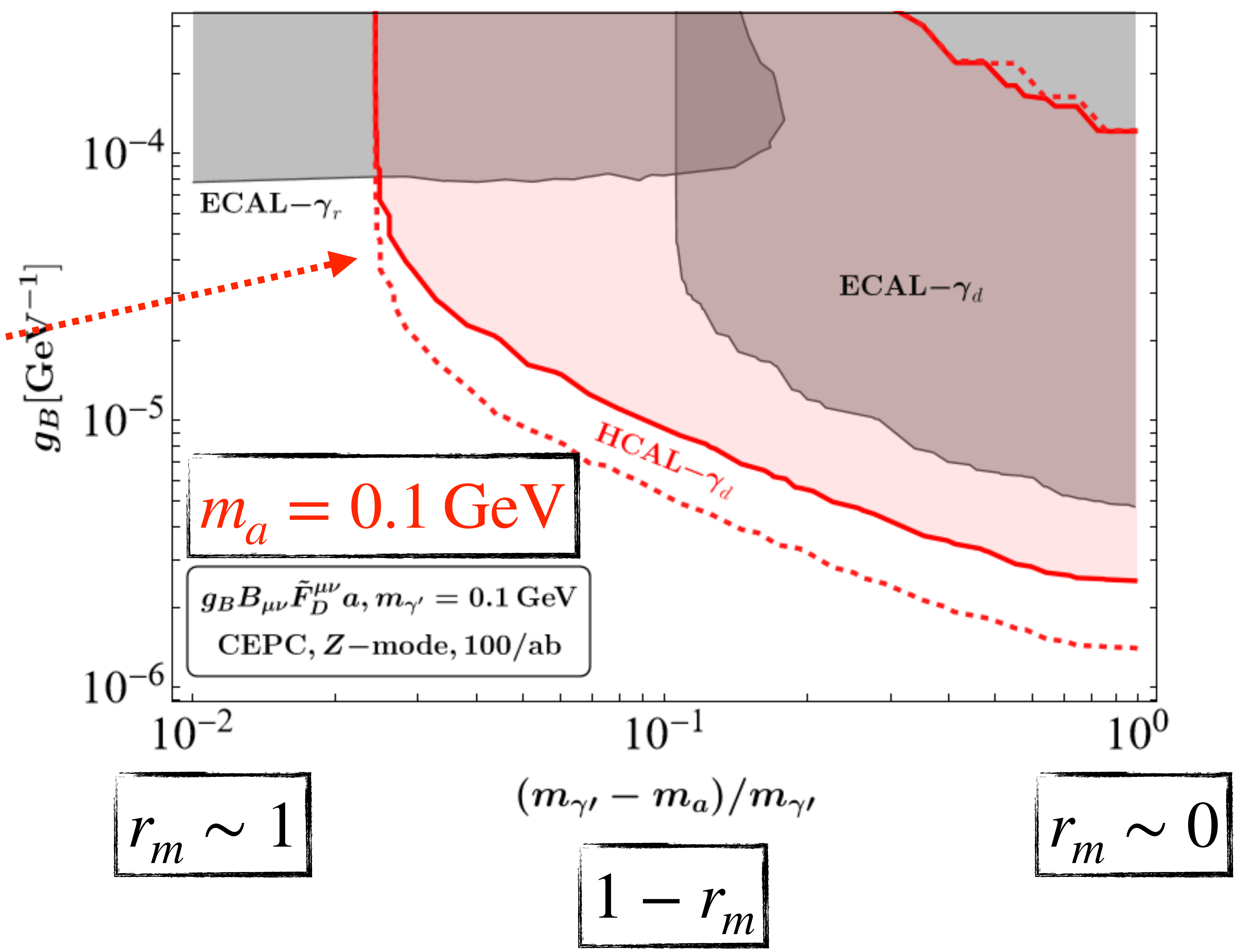


The HCAL-γ_d signature provides exceptional sensitivity to LLPs with decay lengths between ~1 and 10^6 meters and achieves the best sensitivity when $L_D = R_H^{in}$.

CEPC sensitivities on axion portal operator

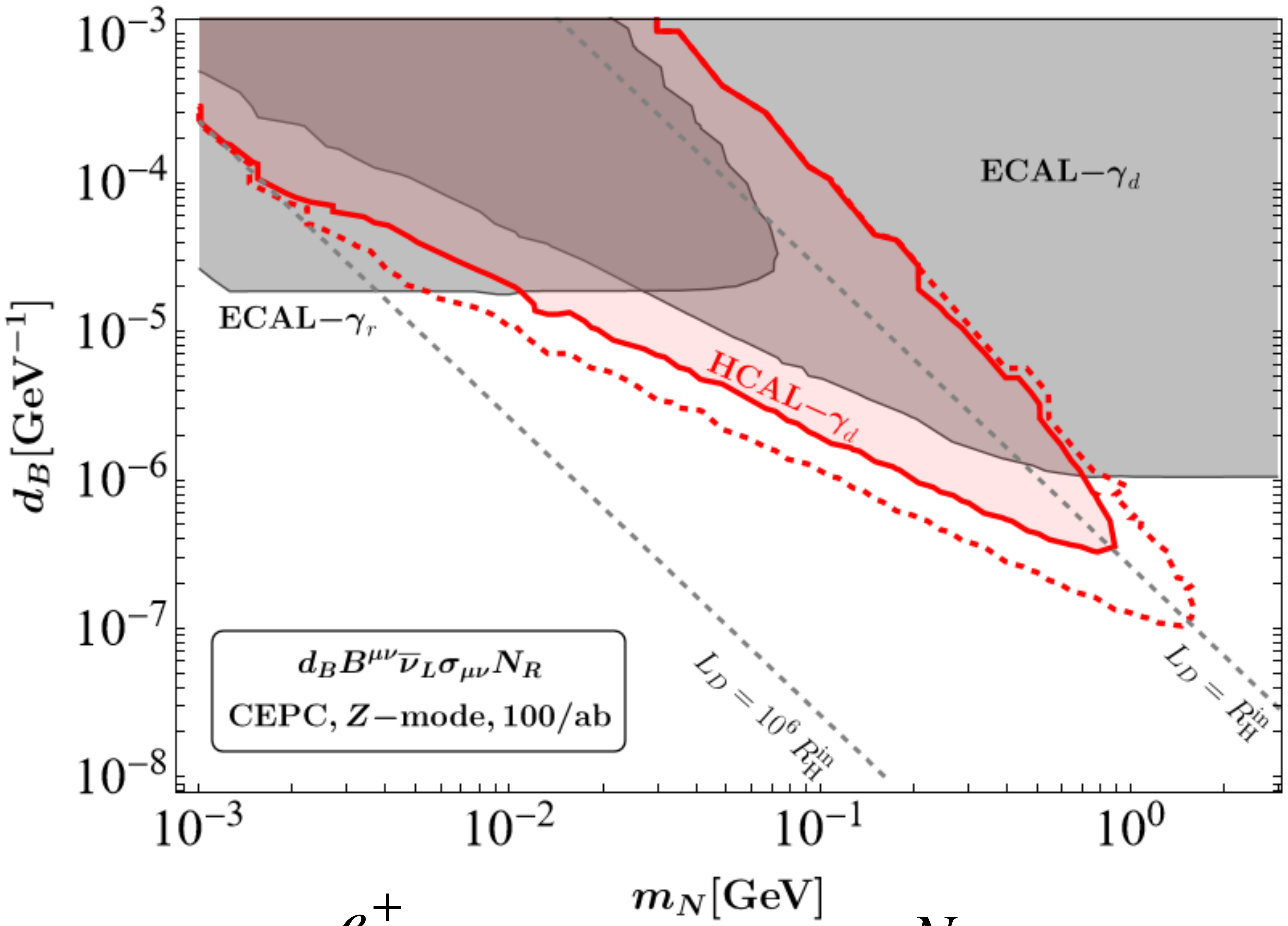
$$E_\gamma^{\max} \simeq \frac{\sqrt{s}}{2}(1 - r_m^2), r_m = m_a/m_{\gamma'}$$

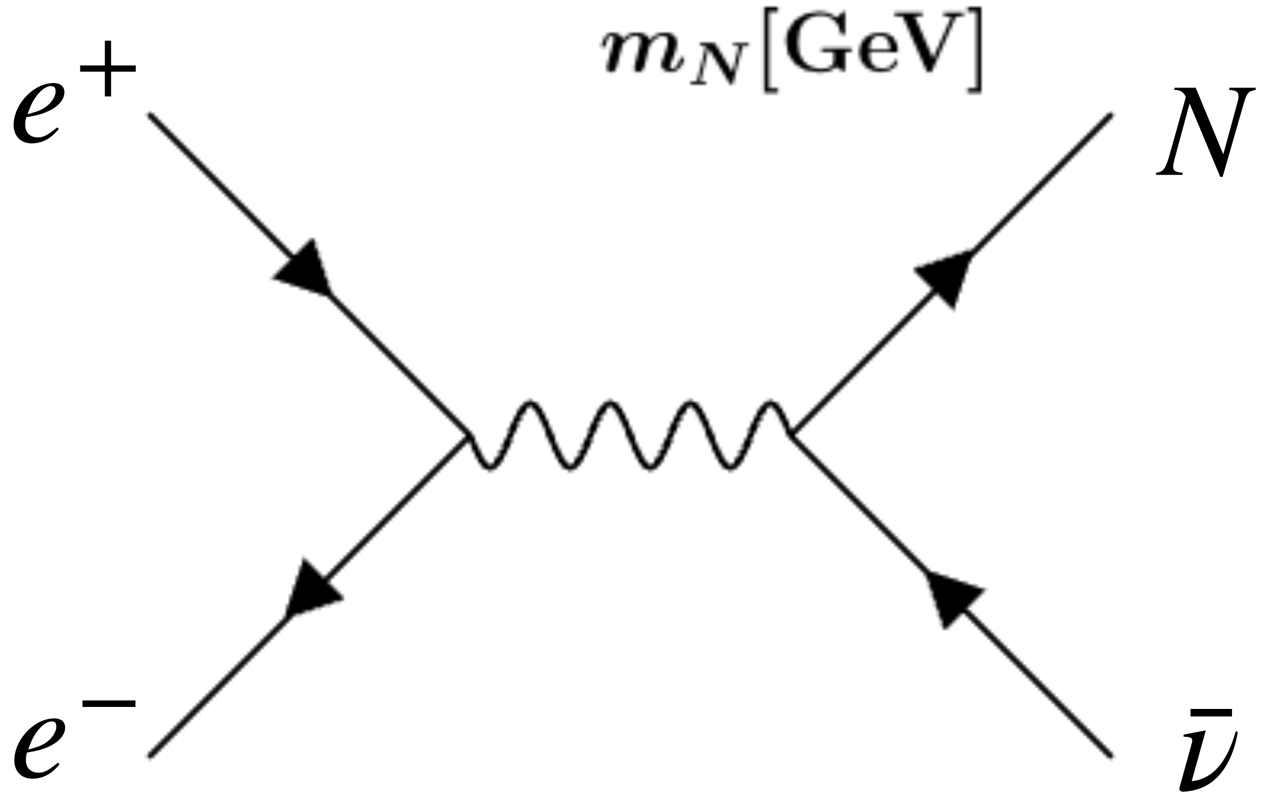




The HCAL-γ_d signature shows better sensitivity for large r_m , but loses sensitivity for $r_m \gtrsim 0.97$ due to the photon energy threshold of the HCAL.

CEPC sensitivities on neutrino dipole portal operator





$r_m = 0$

$$(\bar{L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$$

$$\downarrow$$

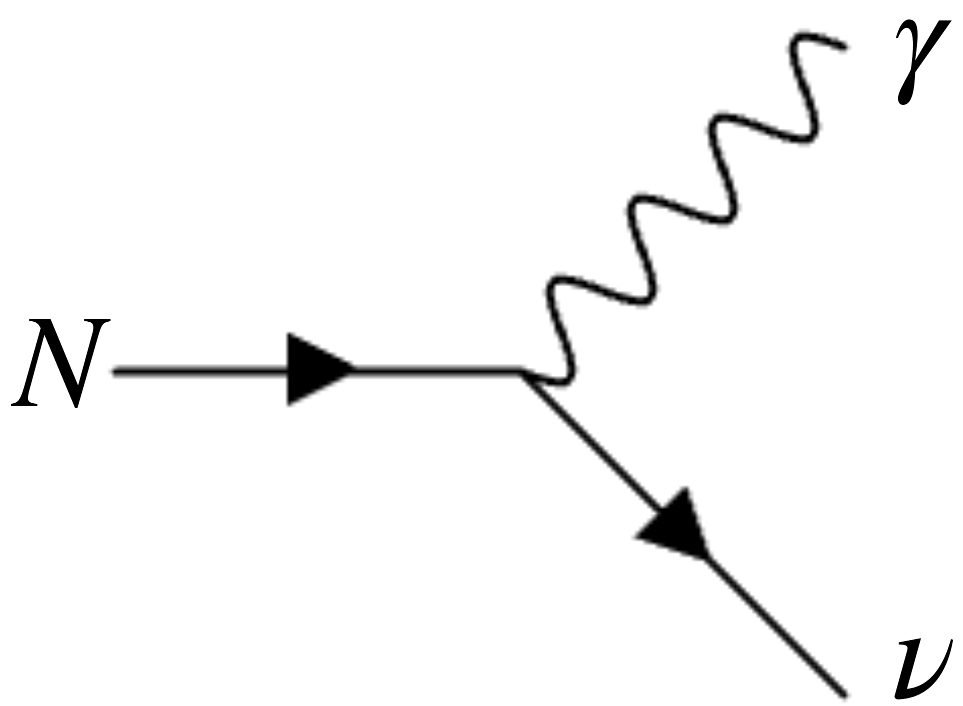
$$\mathcal{O}_{\nu NB} \equiv d_B \bar{\nu}_L \sigma_{\mu\nu} N B^{\mu\nu}$$

N: sterile neutrino

H: Higgs doublet

$B_{\mu\nu}$: hypercharge field-strength tensor

$$\Gamma_{N\to\nu\gamma} = \frac{1}{4\pi} d_B^2 c_W^2 m_N^3$$



Summary

- We propose using the HCAL as a far detector for photons from LLP decays at future Higgs factories, with the forward ECAL acting as a shield against SM particles from the primary vertex.
- The HCAL mono-photon signature provides excellent sensitivity to LLPs with decay lengths between $\sim$1 and 10^6 meters.
- The dominant backgrounds, originating from neutral hadrons produced at the primary vertex, are expected to be efficiently suppressed by particle flow algorithms.
- Next, we plan to compare the HCAL mono-photon sensitivity to photon-portal operators with those of high-granularity directional ECALs and other proposed far detectors.